

| REPORT DOCUMENTATION PAGE   |                  |                               | Form Approved<br>OMB No. 0704-0188                        |   |
|---|------------------|-------------------------------|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b> |                  |                               |   |   |
| 1. REPORT DATE (DD-MM-YYYY)<br>05-04-2011   |                  | 2. REPORT TYPE<br>Proceedings |   | 3. DATES COVERED (From - To)<br>MAR 2011 - APR 2011 |
| 4. TITLE AND SUBTITLE<br>The Lunar Laser Communications Demonstration   |                  |                               | 5a. CONTRACT NUMBER<br>FA8720-05-C-0002                   |   |
|   |                  |                               | 5b. GRANT NUMBER  |   |
|   |                  |                               | 5c. PROGRAM ELEMENT NUMBER                                |   |
| 6. AUTHOR(S)<br>Bryan S. Robinson, Don. M. Boroson, Dennis A. Burianek, and Daniel Murphy   |                  |                               | 5d. PROJECT NUMBER  |   |
|   |                  |                               | 5e. TASK NUMBER   |   |
|   |                  |                               | 5f. WORK UNIT NUMBER                                      |   |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>MIT Lincoln Laboratory<br>244 Wood Street<br>Lexington, MA 02420  |                  |                               | 8. PERFORMING ORGANIZATION REPORT NUMBER                  |   |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>NASA<br>Greenbelt Road<br>Greenbelt, MD 20771  |                  |                               | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>NASA                  |   |
|   |                  |                               | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)                    |   |
| 12. DISTRIBUTION / AVAILABILITY STATEMENT<br>DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.  |                  |                               |   |   |
| 13. SUPPLEMENTARY NOTES   |                  |                               |   |   |
| 14. ABSTRACT<br>The Lunar Laser Communications Demonstration represents NASA's first attempt to demonstrate optical communications from a lunar orbiting spacecraft to an Earth-based ground receiver. A low SWAP optical terminal will be integrated onto the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, presently scheduled to launch in 2013. LLCD will demonstrate duplex optical communications between this small space terminal and a multi-aperture photon-counting ground terminal at downlink data rates of up to 622 Mbps and uplink data rates of up to 20 Mbps.  |                  |                               |   |   |
| 15. SUBJECT TERMS<br>Free-space optical communications, lasercom, photon counting receiver, lunar laser communications demonstration  |                  |                               |   |   |
| 16. SECURITY CLASSIFICATION OF:   |                  |                               | 17. LIMITATION OF ABSTRACT<br>SAR                         | 18. NUMBER OF PAGES<br>4                            |
| a. REPORT<br>U  | b. ABSTRACT<br>U | c. THIS PAGE<br>U             |   |   |
|   |                  |                               | 19a. NAME OF RESPONSIBLE PERSON<br>Zach Sweet             |   |
|   |                  |                               | 19b. TELEPHONE NUMBER (include area code)<br>781-981-5997 |   |

# The Lunar Laser Communications Demonstration

Bryan S. Robinson, Don. M. Boroson, Dennis A. Burianek, Daniel A. Murphy

MIT Lincoln Laboratory  
Lexington, MA, USA  
brobinson@ll.mit.edu

THIS MATERIAL HAS BEEN CLEARED  
FOR PUBLIC RELEASE BY 66 ABW/PA

DATE: 5 Apr 11

CASE # 66ABW 2011-0250

**Abstract**—The Lunar Laser Communications Demonstration represents NASA's first attempt to demonstrate optical communications from a lunar orbiting spacecraft to an Earth-based ground receiver. A low SWAP optical terminal will be integrated onto the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, presently scheduled to launch in 2013. LLCD will demonstrate duplex optical communications between this small space terminal and a multi-aperture photon-counting ground terminal at downlink data rates of up to 622 Mbps and uplink data rates of up to 20 Mbps.

**Keywords**—Free-space optical communications, lasercom, photon counting receiver, lunar laser communications demonstration

## I. INTRODUCTION

In order to support projected data return requirements for future space missions, NASA is developing free-space optical communications technology. In comparison to current radio-frequency communications capabilities, free space optical communications offers the promise of higher data rates with reduced user burden in terms of required size, weight, and power (SWAP) for transmit and receive terminals. As an example, from lunar orbit, a ~10-cm transmit aperture transmitting a 0.5-W optical signal to an Earth-based 0.5-m collection aperture can support a data rates in excess of 500 Mbps using existing technologies. By comparison, on a recent lunar mission, the Lunar Reconnaissance Orbiter, a state-of-the-art radio frequency system designed to support data rates of 100-Mbps downlink rates uses a 75-cm transmit aperture transmitting a 40-W Ka-band signal to an 18-m collection aperture on the Earth. In addition to reduced user burden, transmission in the optical bands offers access to large amounts of unregulated spectrum. Bandwidths in excess of 40 GHz can be utilized with existing electronic and electro-optic technologies. In order to demonstrate these potential benefits of free-space optical communications for future deep space missions,

NASA's Lunar Laser Communications Demonstration (LLCD) will demonstrate many of the potential benefits of free-space optical communications for future deep space missions [1]. LLCD will demonstrate high-rate duplex optical communications between a space terminal in lunar orbit and an Earth-based ground terminal. The LLCD system consists of a space terminal, the Lunar Lasercom Space Terminal (LLST), and a ground terminal, the Lunar Lasercom Ground Terminal (LLGT). The space terminal is will be operated as a payload on the Lunar Atmospheric Dust and Environment Explorer (LADEE) spacecraft [2]. The ground terminal is designed to

be transportable. However, throughout LLCD operations, it will reside at a single location. Site selection for the LLGT is currently underway. The operation of the two terminals are coordinated by Lunar Lasercom Operations Center (LLOC) which is currently planned to be located at Goddard Space Flight Center in Greenbelt, Maryland.

## II. TERMINAL OVERVIEW

### A. Lunar Lasercom Space Terminal

The LLST consists of an optical module and two electronics modules, the modem and the controller electronics, shown in Fig. 1. The optical module is a 4-inch reflective telescope that produces a ~15  $\mu$ rad downlink beam. The telescope is mounted to a two-axis gimbal via a magneto-hydrodynamic inertial reference unit (MIRU) [3]. Angle-rate sensors in the MIRU detect angular disturbances which are then rejected using voice-coil actuators for inertial stabilization of the telescope. Optical fibers couple the optical module to the modem where transmitted optical waveforms are generated and received optical waveforms are processed [4]. Control for the optical module and modem as well as command and telemetry interfaces to the spacecraft are provided by the controller electronics.

### B. Lunar Lasercom Ground Terminal

One of the goals of the LLCD is to demonstrate techniques for aggregating multiple small- to moderate-sized apertures in

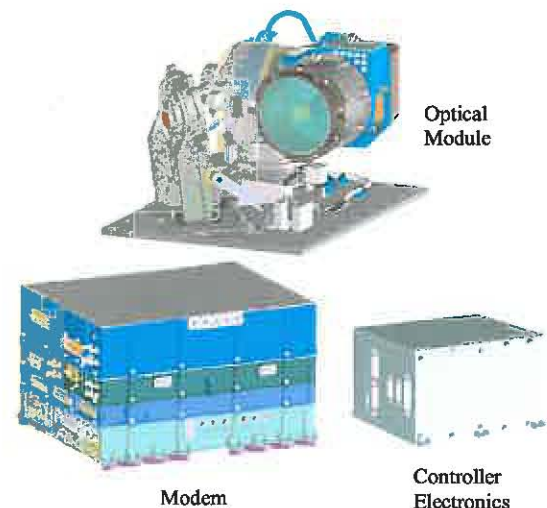


Figure 1. The Lunar Lasercom Space Terminal (LLST)



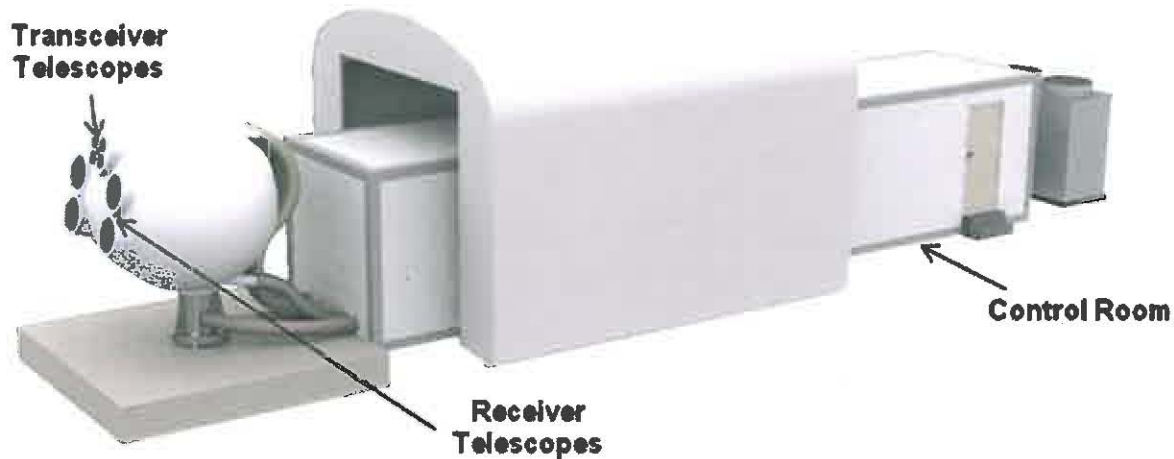


Figure 2. The Lunar Lasercom Ground Terminal (LLGT)

order to create an equivalent large-aperture for transmission and reception of optical signals [5-7]. Thus, the LLGT consists of an array of eight telescopes mounted on a single elevation-over-azimuth gimbal, as shown in Fig. 2. The gimbal provides coarse pointing for the entire telescope array. Each individual telescope includes a wide field-of-view focal plane array detector and a fast steering mirror for fine pointing corrections and tracking the received downlink signal. Four transceiver telescopes are used for transmitting the uplink signal. These  $\sim 15$ -cm refractive telescopes generate a  $\sim 10$ - $\mu$ rad focused beam for transmission. Four 40-cm reflective telescopes are used for the downlink collection aperture.

A control room housed in a 40-foot shipping container provides control for the telescopes and gimbal. The control room also houses the modem electronics and the uplink transmitter and downlink receiver electro-optics. The uplink transmitters and downlink receivers are coupled to the transceiver and receiver telescopes, respectively, via optical fibers.

### III. OPERATIONS

The Lunar Laser Communications Demonstration will operate during the commissioning phase of the LADEE mission. During this phase, the LADEE spacecraft is in a  $\sim 2$ -hour equatorial orbit around the moon. When the moon is in view of the LLGT, there is a  $\sim 65$ -minute window in each orbit when the LADEE spacecraft is in view of the LLGT and LLCD operations can occur. Power and thermal constraints on the spacecraft limit LLST operations to 15-20 minutes during this window. In each of these short operations periods, the terminals will spatially acquire and demonstrate uplink, downlink and time-of-flight operations.

#### A. Spatial Acquisition and Tracking

Prior to initiation of communications, the various pointing and position uncertainties of the LLST and LLGT are sufficiently large so that neither terminal can accurately point its narrow communications beam at the other terminal. Thus, a coordinated spatial acquisition process is required to point the

uplink and downlink beams at their respective receivers. During this process, a defocused  $\sim 45$ - $\mu$ rad beam from the LLGT uplink transceiver telescopes is scanned over the ground terminal pointing uncertainty region. At each step in the scan, the LLGT dwells sufficiently long for the LLST to detect the uplink signal on its wide field-of-view quadrant detector. Once this uplink signal is detected, the gimbal and MIRU actuators on the LLST are used to point the downlink beam back at the LLGT by centering the detected uplink signal on the quadrant detector. Because of the relative motion of the terminals, a point ahead angle is required between the received uplink signal and the transmitted downlink signal. This point ahead angle is implemented using a piezo-electric actuator on the downlink transmitter fiber in the LLST optical module.

The downlink beam is then detected by the LLGT using wide-field of view focal plane array detectors in each of the transceiver and downlink telescopes. While the LLGT gimbal provides coarse pointing for all of the telescopes, a fast steering mirror in each telescope is used for fine pointing corrections as determined by tracking the downlink signal on each of the focal plane arrays. Once tracking of the downlink is initiated, the uplink beam is focused to  $\sim 10$ - $\mu$ rad. This delivers sufficient uplink signal power to the LLST to initiate fine tracking of the uplink using a nutation tracker on the LLST receive fiber.

#### B. Downlink Communications

The downlink communications signal is generated by the LLST modem. Data from multiple sources are multiplexed onto the downlink waveform, including high-rate LLST telemetry ( $\sim 5$  Mbps), high-rate spacecraft data (up to 40 Mbps), and a loopback of the received uplink signal (up to 20 Mbps). Pseudo-random binary sequences are added to the multiplexed data to generate source data rates up to 622 Mbps for transmission. The data from each of these sources are framed and encoded using a 1/2-rate serially-concatenated turbo code which was developed for high-efficiency deep space optical communications [8]. A deep memory buffer (1-2 seconds) is used to interleave the encoded data symbols, providing temporal diversity to help mitigate the effects of atmospheric turbulence on the downlink communications

channel. After encoding and interleaving, the symbols are modulated onto the optical carrier using 16-ary pulse position modulation. The downlink data rate is selectable by varying the pulse-position modulation slot frequency from 311 MHz to 5 GHz. The modulated signal is amplified to 0.5 W using an erbium-doped fiber amplifier. The amplified signal is coupled via single-mode optical fiber to the LLST optical module for downlink transmission.

The downlink signal is collected by the LLGT using the four 40-cm downlink receive apertures. The collected signal in each telescope is coupled into a multimode polarization maintaining fiber for transport to the downlink detectors [9]. Superconducting nanowire detector arrays are used to detect the downlink signal. These single-photon detectors provide high detection efficiency (>50%), low-jitter (<50 ps), low noise (<50 kHz dark count rate), and fast detector response (<15 ns reset time), as required for the high-data rate downlink [10-11]. Each telescope is coupled to a 4-element SNDA. The outputs from each of the SNDAs are digitized and aggregated using high-speed digital electronics. The resulting high-speed digital signal is deserialized and input into a field-programmable gate array (FPGA)-based digital receiver for synchronization, demodulation and decoding.

### C. Uplink Communications

The optical uplink is designed to operate at 10- and 20-Mbps source rates. Two data sources are transmitted on the uplink: commands to the LLST (up to 80 kbps) and high-rate user data for loopback (up to 20 Mbps). These data sources are framed and multiplexed in the LLGT digital electronics. The multiplexed data are encoded and interleaved using the same serially-concatenated turbo code and interleaver that is used for the optical downlink. The uplink uses a 4-ary pulse-position modulation format with 311-MHz slots. Dead time between the transmitted symbols is varied from 12 to 28 slots to select between the two uplink data rates. Four optical transmitters modulate the encoded data onto an optical carrier. The wavelengths of each of the four transmitters are detuned by ~1-GHz so that they can be incoherently combined at the LLST receiver with little power penalty. After modulation, each of the four transmitters then amplifies the signal to 10-W using a high-power erbium-doped fiber amplifier. The amplifier outputs are coupled to the four transceiver telescopes via single-mode fiber. The use of four transmit apertures provides spatial diversity to mitigate the effects of atmospheric turbulence while also enabling the use of commercial amplifier technology to generate the 40-W uplink transmit power.

The transmitted signals are collected by the 10-cm LLST telescope aperture and focused into an optical fiber for processing by the LLST modem. A low-noise erbium-doped fiber amplifier amplifies the received optical signal. The output of the optical amplifier is filtered with a 10-GHz fiber-Bragg grating filter prior to direct detection. A near-optimum hard-decision PPM demodulator [12] demodulates the signal which is then decoded by the LLST modem digital electronics. LLST commands received on the optical uplink are relayed to the controller electronics for execution. These commands as well as the high-rate user data received on the uplink are also looped back on the optical downlink.

### D. Two-Way Time-of-Flight Measurements

In addition to uplink and downlink optical communications, LLCD will demonstrate a technique for utilizing duplex optical signals to perform two-way time-of-flight measurements between the LLGT and the LLST. This is accomplished by linking the uplink and downlink clocks in the LLST and comparing the phase of the transmitted uplink frame clocks and the received downlink frame clocks at the LLGT. A 5-GHz voltage-controlled oscillator (VCO) is used to generate the recovered 311-MHz slot clock in the LLST uplink receiver. This same VCO is used to generate the 5-GHz slot clock for the optical downlink, thereby ensuring that the uplink and downlink slot clocks are phase-locked at the LLST. In order to make the time-of-flight measurements, the uplink and downlink frame clocks must also be synchronized. This synchronization is performed via command after the LLST has acquired the uplink signal. After synchronizing the uplink and downlink clocks in this manner, the LLCD system is capable of measuring the ~2.5-s two-way time-of-flight between the LLST and the LLGT with <200-ps accuracy.

## IV. SUMMARY

NASA's Lunar Laser Communications Demonstration will demonstrate, for the first time, high-rate duplex optical communications between a terminal in lunar orbit and an Earth-based ground terminal. It will also demonstrate the use of duplex optical communications signal for high-accuracy two-way time of flight measurements between the terminals. The space terminal will reside on the NASA's Lunar Atmosphere and Dust Environment Explorer, currently scheduled for launch in 2013.

## REFERENCES

- [1] B. S. Robinson, D. M. Boroson, D. A. Burianek, D. V. Murphy, "Overview of the Lunar Laser Communications Demonstration", Proc SPIE 7923 (2011).
- [2] Lunar Atmosphere and Dust Environment Explorer, National Space Science Data Center, <http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=LADEE>
- [3] J. M. Burnside, S. D. Conrad, C. E. DeVoe, A. D. Pillsbury, "Design of an Inertially-Stabilized Telescope for the LLCD", Proc SPIE 7923 (2011).
- [4] L. E. Elgin, S. Constantine, M. L. Stevens, J. A. Greco, K. Aquino, D. A. Alves, B. S. Robinson, "Design of a High-Speed Space Modem for the Lunar Laser Communications Demonstration", Proc SPIE 7923 (2011).
- [5] D. Fitzgerald, "Design of a Transportable Ground Telescope Array for the LLCD", Proc. SPIE 7923 (2011).
- [6] D. M. Boroson, R. S. Bondurant, and D. V. Murphy, "LDORA: A Novel Laser Communications Receiver Array Architecture", Proc. SPIE 5338, 56-64 (2004).
- [7] J. A. Mendenhall, L. M. Candell, P. I. Hopman, G. Zogbi, D. M. Boroson, D. O. Caplan, C. J. Digenis, D. R. Hearn, R. C. Shoup, "Design of an Optical Photon Counting Array Receiver System for Deep-Space Communications", Proc. IEEE, 95, 2059-2069 (2007).
- [8] B. Moision and J. Hamkins, "Coded Modulation for the Deep-Space Optical Channel: Serially Concatenated Pulse-Position Modulation", JPN Progress Report, 42-161 (2005).
- [9] M. E. Grein, "Design of a fiber-coupled superconducting nanowire detector array system for the LLCD", Proc. SPIE, 7923 (2011).

- [10] E. A. Dauler, B. S. Robinson, A. J. Kerman, J. K. W. Yang, E. K. M. Rosfjord, V. Anant, B. Voronov, G. Gol'tsman, K. K. Berggren, "Multi-Element Superconducting Nanowire Single-Photon Detector", *IEEE Trans. Appl. Supercond.*, 17, 279-284 (2007).
- [11] B. S. Robinson, A. J. Kerman, E. A. Dauler, R. J. Barron, D. O. Caplan, M. L. Stevens, J. J. Carney, S. A. Hamilton, J. K. Yang, K. K. Berggren, "781-Mbit/s photon-counting optical communications using a superconducting nanowire detector", *Opt. Lett.*, 31, 444-446 (2006).
- [12] M. L. Stevens, D. M. Boroson, D. O. Caplan, "A Novel Variable-Rate Pulse-Position Modulation System with Near Quantum Limited Performance", *IEEE Lasers and Electro-Optics Society Annual Meeting*, 301-302 (1999).